Modeling the cost of data communication for multi-node computer networks operating in the United States

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The study reported here examines the cost of data communication for multi-node computer networks operating in the United States. We begin by defining a market basket of private-line transmission services and identifying its constituent prices. Two analytic models are then proposed. The first, which derives a theoretical relationship from microeconomic considerations, gives price movement as a function of the demand for service. The second embodies a learning curve fit to historical data, wherein the slope of this curve (0.71) equals the slope of the historical curve for the advance of integrated-circuit technology. Extrapolations from the two models agree well; moreover, both extrapolations conform to long-established historical trends. These agreements lend plausibility to the idea that the price of data communication unfolds in an orderly way over the long run, and, despite the perturbation introduced by the Bell System divestiture of 1984, future price movements may return to their traditional 11% annual decline.

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Introduction and overview

The cost of data communication has long been recognized as a fundamental influence on the high-level design of data processing equipment and computer networks. This influence is felt, of course, through its economic consequences: the economic consequences of centralized versus distributed processing; the economic consequences of local versus remote storage; and the economic consequences of trades among hardware, firmware, and software embodiments of the communication functions themselves. Nevertheless, the literature is sparse on both the cost of data communication and the factors that have driven this cost to change over time. Here, we address the dearth of information by quantifying, modeling, analyzing, and extrapolating the price of commercial communication services that interconnect geographically diverse, multinode computer networks operating in the United States.

First, we define a market basket of private-line transmission services, and show how the prices of its constituents have changed in the recent past. We then introduce two idealized models and fit their parameters to historical data on prices. When so calibrated, the models lend support to the view that the movement of transmission prices was perturbed by the 1984 divestiture of the Bell System, but that future declines in telecommunication prices could, sometime over the next several years, again fall in line with the long-term historical trend of 11% per annum decline, conditional on the growth of demand for telecommunication services continuing at historical levels.

Of the two models that support this view, the first, called here the *microeconomic model*, works from the conjectures that 1) the market for interstate transmission is now competitive, 2) the demand for communication bandwidth is inelastic with respect to its price, and 3) the carriers can, in theory, provide additional private-line bandwidth at near-zero marginal cost, given today's extensive deployment of high-capacity optical-fiber transmission systems. Together, these points support the derivation of a simple, metaphorical relationship that expresses downward price movements in terms of the rate of increase in demand.

The second model adapts the mathematical learning curve to express change in the price of telecommunication service as a function of cumulative demand. An examination of historical data on the price and volume of toll calls originating in the pre-divestiture Bell System suggests that the slope of the learning curve for the telecommunication industry is 0.71. Because this is the same as the slope of the learning curve for electronic technology reported elsewhere, we entertain the possibility that this particular slope is intrinsic to both industries. Extrapolations from the learning curve with this slope closely match extrapolations from the microeconomic model, which was derived from an independent set of considerations; moreover, both sets of extrapolations are in general agreement with long-established historical trends. We therefore conclude that both models are useful as aids to understanding the evolution of telecommunication prices.

To end the paper, we bring the various elements of the investigation together in an exhibit that shows the movement over time of the cost of exchanging a million octets of data. This exhibit confirms the intuitive notion that the cost of data communication has dropped steadily over the last decade, and seems likely to drop further over the next—absent any trend-altering developments—perhaps at a rate that returns once again to the historical 11% per annum decline.

End-to-end prices

The first step in this investigation is to define tractable proxies for the prices of the private-line transmission services that often interconnect network nodes. For each given transmission speed, this can be done by averaging the prices of links of various lengths that originate and terminate in a variety of locations throughout the United States; doing so in effect specifies a *market basket* for private-line services. Details on the structure of one such market basket are given below, along with the prices of its T1- and T3-rate constituents over the years 1988–1992.

The market basket defined here comprises end-to-end connections, which are those connections that join two instances of a customer's premises. Under the current arrangement in the United States, each such connection often requires the involvement of three telecommunication carriers: one carrier that provides interexchange service, and two carriers that provide the local-access service needed to connect the customer's premises to the interexchange carrier's point of presence, one on each end of the interexchange span. As a convenience to their customers, however, the larger interexchange carriers sometimes act as brokers, procuring the needed local-access services from the appropriate carriers and reselling these services to the end users, thereby providing those users with a single point of contact. In this study, the prices of the various components of the end-to-end connection are taken from the public tariffs that one of the major carriers files with the Federal Communications Commission (FCC) for single-provider end-to-end service; in using this proxy, we do not consider the discount from the established price of interexchange service that is sometimes available to the carriers' largest customers.

Price schedules for the interexchange component of an end-to-end connection have in the past been nonlinear, in the sense that the next-mile charge for a 100-mile circuit was not necessarily the same as the next-mile charge for a 3000-mile circuit, although recently this kind of

nonlinearity has diminished. In response to this historical concern, the method used here for pricing interexchange service exercises a range of possibilities by averaging the prices of eight 100-mile spans, four 500-mile spans, two 1000-mile spans, and one 3000-mile span (520-mile average).

Because price schedules for the local-access component vary from state to state, and sometimes from region to region within a state, the numerous rate structures must be averaged in a way that reflects each region's presence in the extant base of private lines. The method chosen here to address this variation is based on the assumption that business activity, and consequently the use of private lines, is positively correlated with urban population. In accord with this premise, the ten states having the greatest urban populations were identified, and each was assigned a weight proportional to its assumed economic importance. Within each of the ten states, the charge for a representative access circuit was found by adding the costs of eight two-mile circuits, four four-mile circuits, two eight-mile circuits, and one sixteen-mile circuit, again to exercise historical nonlinearities in pricing. The resulting sum for the fifteen circuits was divided by fifteen, to give a distance-weighted average. Ten numbers were then at hand, each representing the distance-weighted price of an access circuit in one of the ten metropolitan states. Each of these ten numbers was multiplied by the economic weight associated with its state, and the products added. The resulting sum represents the cost of an access circuit, distance averaged, and weighted for assumed economic importance [1].

- *Private-line prices 1988–1992*

Recent prices for digital private-line services as given in **Table 1** were determined according to the method outlined above, applied to data taken from FCC tariffs [2, 3]. In establishing these monthly prices, one-time charges were amortized using the standard method for converting a present value to an annuity [4]. The prices in Table 1 include charges for one interexchange circuit, two local-access circuits and their coordination, and two central-office connections; not included are charges for customer-premises multiplexers, DSU/CSUs, and other network-circuit-terminating equipment.

Table 1 Monthly prices of private-line telecommunication services. Prices are given for mid-December of the year indicated.

Year	*End-to-end prices*	
	T1	*T3*
1988	$12,783	$114,670
1989	7,747	79,700
1990	7,680	81,560
1991	7,308	66,030
1992	6,162	55,804

Microeconomic model

We now develop a simple microeconomic model to use as an aid to understanding the effects of supply and demand on telecommunication prices. Economic theory says that a market with free entry will become increasingly competitive; moreover, a critical reading of the business press suggests that the market for interstate telecommunication services may now be operating competitively [5]. Taking this idea one step further, the model developed below works from the premise that the marketplace for telecommunication bandwidth has in fact reached a competitive state, and that the implications of the competitive state suggest how the market might reasonably be expected to behave in the future.

- *Balancing supply and demand*

In the literature on telecommunication economics, there seems to be general agreement that the demand function for telecommunication service is log-linear [6, 7]. Accordingly, let Q be the quantity of bandwidth sold, let p be the monthly unit price of bandwidth, and let α and β be constants; demand is then given as a function of price by

$$\log Q = \log \alpha - \beta \log p,$$

which is equivalent to $Q = \alpha p^{-\beta}$.

Since only relative price movements are of interest here, normalize the equilibrium values to $Q_1 = 1.0$ and $p_1 = 1.0$, which implies that $\alpha = 1.0$, thereby giving the normalized demand function as

$$Q = p^{-\beta}. \tag{1}$$

In this representation, β is the negative of the elasticity of demand with respect to price; consequently, $0.0 < \beta < 1.0$ [8].

Initially the normalized revenue, R_1, is given by the product of unit price and quantity:

$$R_1 = p_1 Q_1 = 1.0.$$

Now suppose that the carriers reduce prices to stimulate demand, which results in a move along the demand curve to the new point $(\hat{Q}_1, \hat{p}_1)$. Once again, revenue is given by the product of price and quantity:

$$\hat{R}_1 = \hat{p}_1 \hat{Q}_1 = \hat{p}_1(\hat{p}_1^{-\beta}) = \hat{p}_1^{(1-\beta)}.$$

Since $0.0 < \beta < 1.0$ and $\hat{p}_1 < 1.0$, revenue to the carrier drops with this move; i.e., $\hat{R}_1 < 1.0$. This sets up an untenable situation. With the unfolding of competition, economic theory holds that profits move toward zero (here, *profit* has a special meaning that indicates earnings above the opportunity cost of capital; some authors call

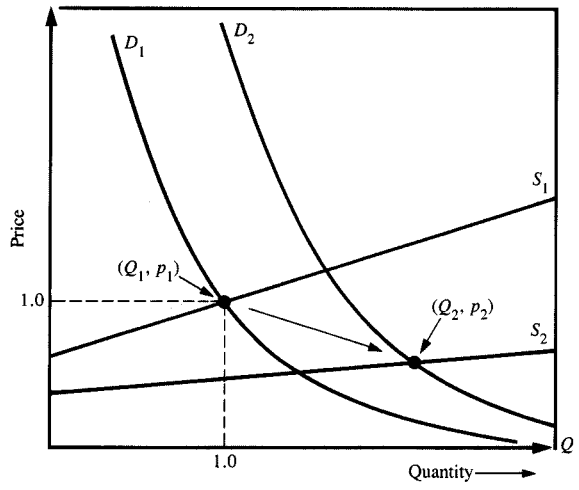

Figure 1

A change in both supply and demand: At the new equilibrium point (Q_2, p_2), revenue is preserved, but prices are lower and quantities are higher than at equilibrium point (Q_1, p_1).

such earnings *supernormal profits*). Clearly, the carrier's costs do not decrease as a result of increasing the supply of bandwidth. At some point, further reduction in total revenue caused by a drop in price or, equivalently, an increase in supply drives supernormal profits below zero, to a new level that cannot be sustained.

• *Price movements*

Now suppose that the market demand for bandwidth changes, as represented in **Figure 1** by the shifting of the demand function from D_1 to D_2. If the carriers increase the supply of bandwidth, the market moves to the point shown in Figure 1 as (Q_2, p_2).

Revenue is now $R_2 = p_2 Q_2$. Given the present abundance of latent bandwidth in the public network resulting from the widespread deployment of optical fibers, the carriers should be able to increase supply to the private-line market at near-zero marginal cost [9]. Consequently, the carriers can maintain zero supernormal profits if the revenue at the new operating point is equal to the revenue at the old operating point, or if $R_2 = 1.0$. Thus, in theory the price can fall by the factor $1/k$ if the demand for bandwidth increases by a factor of k, or

$$p_2 = \frac{p_1}{k}. \tag{2}$$

To introduce time as a parameter in Equation (2), let r_B be the compound annual growth rate of the demand for private-line bandwidth, and let N be the number of years of growth at this rate. Then,

$$(1 + r_B)^N = k.$$

Substituting this relationship into Equation (2) gives

$$p_2 = \frac{p_1}{(1 + r_B)^N}. \tag{3}$$

Beyond the issue of supply and demand, and beyond the issue of inexpensive bandwidth through fiber optics, the telecommunication industry has traditionally realized annual productivity improvements of the order of a few percent; let $\hat{r}$ be the annual rate of this productivity improvement. Factoring $\hat{r}$ into Equation (3) gives the final form of the microeconomic model:

$$p_2 = \frac{p_1}{(1 + r_B + \hat{r} + r_B\hat{r})^N}. \tag{4}$$

• *Calibrating the microeconomic model*

Historical data gathered by the Federal Communications Commission [10] suggest that the carriers' annual productivity improvement is about 2.5%, giving $\hat{r} = 0.025$. According to other reports [11], the traffic mix on large, private networks was roughly 27.4% data, 72.6% voice in 1988. If data traffic grows at an annual rate of 23% and voice grows at an annual rate of 2%, as suggested by historical trends for the public network, an extrapolation from this basepoint says that the aggregate bandwidth demanded by these customers should increase by a factor of 1.57 from 1988 to 1993, giving an annual rate of increase of $r_B = 0.095$. Although this exercise is most assuredly inexact, the end result, an annual increase in private-network traffic of about 9.5%, is clearly plausible. With these parameter values, Equation (4) shows that the annual compound price decrease supported by the microeconomic model is approximately 10.9% in constant dollars.

Learning-curve model

As a complement to the microeconomic model, we now entertain the possibility of modeling change in the price of specific telecommunication services by the mathematical formulation known as the *learning curve*, or, more precisely, the *univariate* learning curve. The learning curve has long been used to quantify the relationship between product cost and cumulative product volume: According to empirical evidence, costs normally drop by a constant percentage each time the cumulative volume of a product doubles.

Badiru reviews the many variants of the learning curve [12]; below, we derive a variant that has time as a common

parameter linking price and cumulative volume. We then examine historical data on the price and the yearly number of toll calls originating in the Bell System over the years 1968–1980, a period chosen to avoid the distortions introduced by the post-divestiture transition from regulated to competitive marketplace, and a period over which the cumulative volume of toll calls twice doubled. From these pre-divestiture data, we deduce the slope needed to fit the learning curve to the behavior of the interexchange telecommunication industry. Because the slope of the learning curve derived for the interexchange operation of the Bell System turns out to be the same as the historical slope of the learning curve for basic electronic technology, we assume that this particular slope is intrinsic to both industries, and that a learning curve with this slope can be a useful aid to understanding the movement of telecommunication prices.

• *Learning curve*

The learning curve can be stated mathematically as an elasticity equation:

$$\frac{dC}{dV} = -m\frac{C}{V},$$

where V is cumulative volume, C is unit cost, and m is a constant of proportionality. Separating the variables and integrating from V_a to $V_b = 2^n V_a$, where n is the number of times cumulative volume has doubled in going from cost C_a to C_b, and then simplifying the result, gives

$$\ln\left(\frac{C_b}{C_a}\right) = -mn \ln 2. \tag{5}$$

Using the properties of logarithms, we can write Equation (5) as $C_b = e^{-mn \ln 2} C_a$. For $n = 1$, or one doubling of volume, the slope of the learning curve is defined as $S = e^{-m \ln 2}$, or, equivalently,

$$m = -\frac{\ln S}{\ln 2},$$

which, when substituted into Equation (5), gives

$$\ln\left(\frac{C_b}{C_a}\right) = n \ln S. \tag{6}$$

We know, however, that

$$\frac{V_b}{V_a} = 2^n,$$

or, equivalently, that

$$n = \frac{1}{\ln 2}\ln\left(\frac{V_b}{V_a}\right). \tag{7}$$

Table 2 Number of toll calls originating in the Bell System.

Year	*Billion calls*
1968	7.8
1969	9.1
1970	10.0
1971	10.5
1972	11.6
1973	12.4
1974	13.3
1975	16.8
1976	19.1
1977	21.5
1978	24.7
1979	27.9
1980	29.7

Substituting (7) into (6) gives

$$\ln\left(\frac{C_b}{C_a}\right) = \left[\frac{\ln S}{\ln 2}\right]\left[\ln\left(\frac{V_b}{V_a}\right)\right]. \tag{8}$$

Let R denote the compound annual growth rate of yearly volume; cumulative volume after N years of growth at this rate is then given by

$$V_b = V_a\left[\frac{(1+R)^N - 1}{R}\right], \tag{9}$$

where V_a is the first-year volume. Substituting Equation (9) into Equation (8) gives

$$\ln\left(\frac{C_N}{C_1}\right) = \left[\frac{\ln S}{\ln 2}\right]\left[\ln\left(\frac{(1+R)^N - 1}{R}\right)\right],$$

where C_N is the unit price after N years of growth. Since we are interested in relative prices, let $C_1 = 1.0$. The foregoing can then be solved for C_N:

$$C_N = \left(\frac{(1+R)^N - 1}{R}\right)^{-m}. \tag{10}$$

• *Calibrating the learning curve model*

Table 2 shows the yearly number of toll calls originating within the Bell System over the years 1968–1980 [13]. Fitting a linear regression to the logarithm of the yearly number of calls gives the following result:

$$K_Y = 0.0323 \times 10^{0.0494(Y-1920)},$$

where K is the number of toll calls (billions) in the year Y. In this representation, the year 1920 has been chosen as the reference point in order to simplify the computation of cumulative totals. In effect, we assume that the number of toll calls before 1920 is negligible compared with more recent cumulative data, and may therefore be ignored safely.

Table 3 Monthly price of a 520-mile T1 circuit in constant 1992 dollars.

Year	*Historical*	*Extrapolations*	
		Learning curve	*Micro*
1988	$15,039	$10,603	$9,777
1989	8,682	9,119	8,711
1990	8,174	7,939	7,762
1991	7,535	6,974	6,916
1992	6,162	6,162	6,162
1993	—	5,470	5,490
1994	—	4,876	4,892
1995	—	4,355	4,359
1996	—	3,899	3,884
1997	—	3,496	3,460
1998	—	3,140	3,083
1999	—	2,822	2,747
2000	—	2,540	2,448

Learning curve: $S = 0.71$, $R = 0.23$, initial service year = 1984.
Micro: Microeconomic model; annual decline of about 10.9%.
Mid-December prices are given.

Table 4 Monthly price of a 520-mile T3 circuit in constant 1992 dollars.

Year	*Historical*	*Extrapolations*	
		Learning curve	*Micro*
1988	$134,909	$107,740	$88,543
1989	89,320	88,256	78,892
1990	86,804	74,523	70,293
1991	68,077	64,098	62,631
1992	55,804	55,804	55,804
1993	—	49,020	49,721
1994	—	43,311	44,302
1995	—	38,451	39,473
1996	—	34,273	35,170
1997	—	30,612	31,337
1998	—	27,406	27,921
1999	—	24,572	24,878
2000	—	22,069	22,166

Learning curve: $S = 0.71$, $R = 0.23$, initial service year = 1986.
Micro: Microeconomic model; annual decline of about 10.9%.
Mid-December prices are given.

Let the cumulative number of toll calls between the years 1920 and M be denoted V_M:

$$V_M = 0.0323 \sum_{j=1921}^{M} 10^{0.0494(j-1920)}.$$

Accordingly, the approximate accumulated totals are $V_{1968} = 70.4$ billion toll calls from 1921 to 1968, and $V_{1980} = 276.5$ billion from 1921 to 1980. Consequently,

$$\frac{V_b}{V_a} = \frac{V_{1980}}{V_{1968}} = \frac{276.5}{70.4} = 3.93.$$

The price of a one-minute, 500-mile toll call originating in the Bell System over the years 1968–1980, found by fitting a linear regression to the logarithm of historical data [14], is given in constant-dollar units (cents) by

$$\hat{P}_Y = 122 \times 10^{-0.0243(Y-1968)}.$$

From this regression, we have

$$\frac{C_{1980}}{C_{1968}} = \frac{\hat{P}_{1980}}{\hat{P}_{1968}} = \frac{62.3}{122.0} = 0.511.$$

With the results computed above for the period 1968–1980, Equation (8) can be solved for S to give an estimate of the slope of the learning curve that relates price and cumulative volume for the telecommunication industry: $S = 0.71$.

• *Long-term price movements*

Substituting the values $S = 0.71$ and $R = 0.23$ into Equation (10) and taking the limit as N approaches infinity suggests a long-term trend line of 9.7% annual decline in the price of transmission service [15]. Since the trend line is approached monotonically from above, however, the annual decline for finite values of N will be greater than 9.7%. Using the calibration just described and computing C_N/C_{N-1} from Equation (10) shows, for example, price drops of 11.2% in the tenth year of service and 9.9% in the twentieth.

The cost of data communication—A composite view

The foregoing sections develop a microeconomic model and a learning curve that embody various assumptions about how and why telecommunication prices change. Before considering further the implications of these models, let us choose year-end 1992 as the reference for prices and calibrate the two models accordingly; the years for the start-up of the learning curves are 1984 and 1986, respectively, for T1 and T3 service. Extrapolations from Equations (4) and (10) so calibrated are given for T1-rate circuits in **Table 3** and for T3-rate circuits in **Table 4**; both tables also restate historical prices in constant 1992 dollars.

We now develop a composite that shows the prices of the various data communication services, as well as how these prices compare with one another and how they have changed over time. For the sake of completeness, we first consider the price of exchanging data over the public switched network using analog modems. The results are then gathered and exhibited in **Figure 2**, where the historical and extrapolated costs of exchanging a megabyte (eight million bits) of data are plotted for the years 1970–2000.

• *Analog modems and switched circuits*

Expanding the scope of the discussion to include analog modems operating over the public switched network

introduces a new consideration: With digital links, the rate of data transmission depends only on the capability of the underlying carrier service, whereas with analog links, the rate of the modem determines the rate of data transmission. Moreover, it is problematic to associate a particular transmission rate with a particular year. Nevertheless, let us adopt the following schedule for the historical advance of transmission rate [in bits per second (bps)] by means of analog modems operating over good-quality switched circuits; also shown is the price of a 500-mile switched circuit, in constant 1992 dollars, expressed in cents per minute (cpm):

- 1970 — 4800 bps, 107 cpm.
- 1975 — 9600 bps, 88 cpm.
- 1980 — 9600 bps, 60 cpm.
- 1985 — 9600 bps, 36 cpm.
- 1990 — 14 200 bps, 20 cpm.
- 1995 — 24 000 bps, 15 cpm (hypothetical).
- 2000 — 24 000 bps, 10 cpm (hypothetical).

Although this list is indeed somewhat arbitrary, it reports the dates of ordinary commercial use of the various modem technologies, as opposed to the dates of prototypes or experimental devices.

• *The cost of exchanging a million bytes of data*

As a common measure, the cost of exchanging a million bytes of data each way over a bidirectional 520-mile circuit may be used to compare the economics of the various transmission services. In making this comparison, let us assume that the business month has 176 hours (22 eight-hour days), and that the links are used 100% during this time, although in this analysis link utilization is a relative consideration that has little absolute bearing. Figure 2 recasts the data from Tables 3 and 4, along with the data on analog modems, to show bidirectional transmission costs in cents per megabyte (plotted on a logarithmic scale) against time (plotted on a linear scale). Throughout, the results are given in constant 1992 dollars; i.e., the effects of inflation have been removed from the historical data, and have not been considered in the extrapolations.

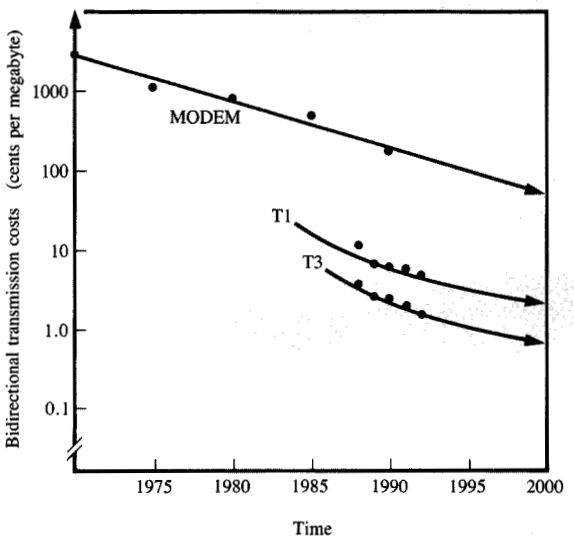

Figure 2

A composite view: The vertical axis shows bidirectional transmission costs in cents per megabyte, on a logarithmic scale, for a 520-mile link; the horizontal axis shows time on a linear scale.

Discussion and analysis

• *Discussion of the microeconomic model*

The microeconomic model was characterized above as *metaphorical* in order to emphasize its strengths and its limitations. The limitations are plain enough: This model is too simple a construction to capture the full interaction of economics, politics, and technology that in reality determines telecommunication prices. Other models proposed by other investigators attempt to deal with the full range of this interaction by using the tools of econometrics and the deeper aspects of economic theory. These more sophisticated models, unfortunately, also have their limitations, which are discussed in a monograph-length tutorial by Kiss and Lefebvre [16], who review the literature concerning econometric models of telecommunication firms, describe that body of literature as "chaotic," and characterize the essential nature of the studies as "polemic" and fraught with conceptual and technical difficulties.

McCloskey [17] offers a way to see through this fog by suggesting that economic models be thought of as useful combinations of fact, logic, metaphor, and story, with each model expressing a different point of view. Further, he notes that "One group of economists favors simple models because they are more understandable; another group favors complex models because they are more complete." The microeconomic construction proposed here is a simple model that tells a useful story; that is its strength. Below, we entertain the question of how well its story conforms to reality.

• *Discussion of the learning-curve model*

The learning curve was presupposed to fit the problem considered here; its slope ($S = 0.71$) was then derived from historical data on the interexchange operation of the Bell System. It is important to note that this slope

compares favorably with the slopes of the learning curves reported by Cunningham [18] for other industries; moreover, the learning curve for integrated-circuit technology has a slope of 0.72. Because the telecommunication learning curve has virtually the same slope as the learning curve for basic electronic technology [19], it is plausible to think that this slope is intrinsic to both the electronics and the telecommunication industries, and that the learning curve with this slope can be used to gain insight into how telecommunication prices unfold. The plausibility of this assumption is supported further by the near agreement between extrapolations from the learning curve and extrapolations from the independently derived microeconomic model: One suggests an annual decline of 11.2% in the tenth year, ultimately approaching an annual decline of 9.7%, whereas the other suggests an annual decline at the constant rate of 10.9%.

Comparing the models with historical reality

As an alternative to the models proposed here, a linear regression could be fit to the logarithm of the observed or historical constant-dollar prices in Table 3:

$$P = 12\,770 \times 10^{-0.0836(Y-1988)}. \tag{11}$$

Equation (11) would imply an annual price decline of 17.5% for T1-rate circuits (the corresponding figure would be 18.4% for T3-rate circuits, based on historical data from Table 4). An examination of the data in Table 3 suggests, however, that the rapid drop in price that began just after divestiture was in abeyance by year-end 1989. Consequently, Equation (11) may have little long-term importance. It would thus appear that something may have changed within the marketplace during 1989.

What happened, or so we argued earlier, was that the interexchange industry reached a competitive state. This suggests that the rapid declines in prices from 1984 to 1989 were partly the result of the one-time transition from an industry dominated by a regulated monopoly to an industry having a plurality of competitors, and therefore these declines cannot be attributed wholly to ongoing, sustainable improvements in technology and operations. In this interpretation, the shrinking wedge between observed prices and the learning-curve prices may be seen as the closing gap between monopoly and a competitive environment, where monopoly prices may have begun their decline from an artificially high level. Consequently, the movement of prices after 1989 should be fundamentally different from their movement before 1989—hence, there is no need for either the microeconomic or the learning-curve model to agree with historical prices before 1989, as neither model purports to capture the one-time transition.

From 1989 onward, prices computed from the two models agree in approximation with each other and agree in approximation with recent historical data. Moreover, trends suggested by the models conform to the 11% annual long-term decline in the price of data communication reported by Branscomb [20] in 1979. Although these agreements are reassuring, and although they help build the case argued here, clearly they offer no guarantee that either of the models would prove clairvoyant in telling the future.

The models can, however, make a claim to explaining the recent past. The legitimacy of this claim can be evaluated by a statistical analysis wherein the observed price is paired with the predicted price for each year. In order to judge whether one variable carries useful information about the other—i.e., whether the model has good explanatory or (retrospective) predictive power—the match between predicted prices and observed prices can be judged for the years in which historical data are now available. Because the models have been constructed by theoretical argument rather than by curve fitting, the set of predicted prices retains several degrees of freedom with respect to the set of observed prices. Consequently, predictive power can be measured by the coefficient of correlation.

Determining the coefficient of correlation

- Let x_i be the ith predicted point.
- Let y_i be the ith observed point.
- Let $\bar{x}$ be the mean value of the predicted points.
- Let $\bar{y}$ be the mean value of the observed points.
- Let n be the number of points.

The coefficient of correlation is given by

$$r = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2}}. \tag{12}$$

Using the learning-curve data in Table 3 for the years 1989–1992, Equation (12) gives the result $r = 0.95$ ($r = 0.96$ for the microeconomic model). The corresponding coefficient of determination is $r^2 = 0.90$ ($r^2 = 0.92$), suggesting that the model accounts for nearly all of the variation in the observed data.

Not enough historical points are yet available to establish a useful confidence interval around the purported value of the coefficient of correlation. We do, however, have enough data to reject with more than 97% statistical confidence the null hypothesis, "the model has no explanatory power." This goes as follows: The t-statistic is given by

$$t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}}.$$

Here, $n = 4$, the number of samples; the appropriate arithmetic gives $t = 4.3$. The null hypothesis ($r = 0$) is rejected in favor of the alternative hypothesis $r > 0$ provided $t > t_{\alpha,n-2}$. According to standard statistical tables, $t_{0.97,2} < 4.3$; therefore, we reject the null hypothesis $r = 0$ and its antecedent, "the model has no explanatory power," with more than 97% statistical confidence.

Concluding remarks

This study of the cost of data communication began by defining a market basket of commercial transmission services, thereby quantifying transmission prices so that they could be recorded, tracked, and extrapolated. Two independent models that embodied the history of price movements were then proposed: a microeconomic supply-and-demand model, and a learning curve. Figure 2 brought the various aspects of the work together by showing historical price movements and their extrapolations given in terms of the constant-dollar cost, per megabyte, of exchanging data. The resulting composite suggested that the price of the commercial data communication services that are often used to interconnect geographically diverse, multi-node computer networks has dropped steadily and considerably over time; moreover—to the extent that the past is a useful guide to the future—the cost of data communication seems likely to continue to drop in the future.

The results of the study appear to be cohesive in five significant ways: 1) extrapolations by the learning curve and extrapolations by the microeconomic model agree in approximation; 2) predicted prices and observed prices agree in approximation for the years in which historical data are now available; 3) the recent rate of decline in the price of high-speed transmission over private digital lines and the historical rate of decline in the price of transmission by analog modem agree in approximation; 4) the slope of the learning curve for transmission service and the slope of the learning curve for electronic technology agree in approximation; and 5) the outcome of a t-test is favorable for the coefficient of correlation relating predicted and observed data, although this aspect of the analysis is supported by only scant data. Thus, the evidence as presented here lends plausibility to the idea that data communication prices unfold in an orderly way—at least over the long term—and that the movement of these prices may return to their historical trend of 11% annual decline.

Although it is encouraging to see that the evidence presented here holds together well, this evidence provides no guarantee whatever that either model would prove capable of telling the future. After all, the models offer nothing more—and nothing less—than a mathematical embodiment of one view of history.

References and notes

1. At present, local access for T3-rate service is provided on a case-by-case basis. Consequently, a different approach to finding a representative average was needed for T3. Lacking any more elegant way to proceed, in 1988 I set a price based on a subjective assessment of the specific cases given in the public tariff, and have subsequently adjusted this price only in response to changes in access-coordination or central-office-connection charges.
2. "Tariff F. C. C. Number 9: Private Line Services," AT&T Communications, Bridgewater, NJ, for years 1988–1992.
3. "Tariff F. C. C. Number 11: Private Line Local Channel Services," AT&T Communications, Bridgewater, NJ, for years 1988–1992.
4. I assumed an 11.5% per annum cost of capital and a 60-month project life, and have retained that cost of capital so that changes in interest rates would not induce phantom changes in the price of telecommunication service. Given the recent, substantial decline in interest rates, the wisdom in retaining this figure can be challenged; nevertheless, the prices developed here are not sensitive to the assumed cost of capital, as the one-time charges expressed as an annuity are thoroughly dominated over the course of a 60-month project by other charges that recur monthly.
5. See for example "US Sprint's Latest Round," *Communications Week*, September 11, 1989; "Carriers Battle," *Communications Week*, July 23, 1990; "US Sprint's Troubles Come Amid Ferment in Long-Distance Field," *Wall Street Journal*, July 31, 1990; "Voice Economics: The Big Squeeze on T1-Vendors," *Data Communications*, July 1990, p. 82.
6. B. E. Davis, G. J. Caccappolo, and M. A. Chaudry, "An Econometric Planning Model for American Telephone and Telegraph Company," *Bell J. Economics & Management Science* **4**, No. 1, 29–56 (Spring 1973).
7. S. C. Littlechild, *Elements of Telecommunications Economics*, Peter Peregrinus, Ltd., Stevenage, U.K., 1979.
8. Elasticity is defined as proportional change in demand divided by proportional change in price:

$$\eta_D = \frac{dQ}{dp}\frac{p}{Q}.$$

Operating accordingly on Equation (1) shows that $\eta_D = -\beta$. Thus, the claim that $0.0 < \beta < 1.0$ is equivalent to a claim that the demand for telecommunication bandwidth is inelastic. Economic theory says to expect inelastic demand in markets where substitutes are not readily available, such as the telecommunication market; furthermore, empirical evidence favors the assumption of inelastic demand. For sample values of the elasticity coefficient, see Davis [6] as well as L. S. Hyman, R. C. Toole, and R. M. Avellis, *The New Telecommunications Industry: Evolution and Organization*, Vol. 1, Public Utilities Reports, Inc., Arlington, VA, 1987.
9. This distinction is only a matter of degree. B. M. Mitchell and I. Vogelsang (*Telecommunications Pricing: Theory and Practice*, Cambridge University Press, Cambridge, U.K., 1991), writing about the unusual economic situation of the communication carriers, note that "Up to the available capacity, additional output can be produced at negligible additional cost." The introduction of fiber optic technology to the private-line transmission plant effectively raises the available capacity of that plant virtually without limit.
10. "FCC to End Regulation of AT&T Profit," *Wall Street Journal*, March 17, 1989.
11. Precise, credible measures for the voice-data split and the growth of voice and data traffic are not readily available.

Here, I use the split given in "Communications Forces a Change," *Information Week*, February 20, 1989, pp. 53–56. The 23% growth rate for data traffic is from D. A. Dunn and M. G. Johnson, "Demand for Data Communications," *IEEE Network*, May 1989, pp. 8–12. The corresponding estimate for voice traffic is from "Bellcore Regroups," *Communications Week*, July 30, 1990, p. 12, which quotes Richard Caruso, Vice President of Information Networking Services, Bell Communications Research, Inc; I have used the low end of Caruso's 2–3% estimate in this study.

12. A. B. Badiru, "Computational Survey of Univariate and Multivariate Learning Curve Models," *IEEE Trans. Engineering Management* **39**, No. 2, 176–188 (May 1992).
13. *Statistics of Communications Common Carriers*, Federal Communications Commission, Washington, DC, 1968–1980 editions.
14. Regression fit to data appearing in "Rewiring the World," *The Economist*, October 17, 1987.
15. This assumes that the volume growth rate of T1 and T3 private lines is 23% per annum, which is the figure for the growth rate of data traffic used in computing the 9.5% per annum growth of aggregate bandwidth—see [11]. The 9.5% rate applies to an aggregate taken over the full spectrum of services, whereas the 23% rate applies to one element of this aggregate.
16. F. Kiss and B. Lefebvre, "Econometric Models of Telecommunications Firms," *Revue Economique*, pp. 307–373 (March 1987).
17. D. N. McCloskey, *If You're So Smart: The Narrative of Economic Expertise*, University of Chicago Press, Chicago, IL, 1990.
18. J. A. Cunningham, "Using the Learning Curve as a Management Tool," *IEEE Spectrum* **17**, No. 6, 45–48 (June 1980).
19. This means that the price of telecommunication service and the price of electronic technology fall the same percentage each time the respective cumulative volumes double; it does not mean that the two prices fall at the same annual rate.
20. L. M. Branscomb, "Computing and Communications—A Perspective of the Evolving Environment," *IBM Syst. J.* **18**, No. 2, 189–200 (1979).

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